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CAPTURE CROSS SECTION AND GAMMA-RAY SPECTRUM CALCULATIONS FOR MEDIUM-WEIGHT NUCLEI

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CAPTURE CROSS SECTION AND GAMMA-RAY SPECTRUM CALCULATIONS FOR MEDIUM-WEIGHT NUCLEI*

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We have applied a double-peak, energy-dependent Breit-Wigner model of the E1 gamma-ray strength function to nuclei from As to Rh, to predict their neutron capture cross sections and capture gamma-ray spectra. We found that a consistent set of model parameters could be obtained in this mass region to describe the step in the low-energy tail of the E1 strength function. This step allows: (a) agreement with photonuclear data at high energies, (b) the correct Γ_γ to be obtained for agreement with neutron capture cross-section data, and (c) the calculation of the observed hardness in the capture gamma-ray spectra. For nuclei at or near the closed, N=50 shell, however, the model's double-peak assumption breaks down. In these cases, good results are still obtained if the same set of model parameters is applied except that the E1 strength function is formulated in terms of the first, narrower peak.

[Calculated E1 γ-ray strength functions, calculated $\sigma(n,\gamma)$ and γ-ray spectra for ^{75}As, ^{93}Nb, and ^{103}Rh, calculated $\sigma(n,\gamma)$ for ^{89}Y and ^{90}Zr.]

Introduction

We are continuing to develop our capability to calculate neutron-induced capture cross sections and capture gamma-ray spectra for both stable and unstable medium-weight nuclei. Our earlier modeling work in this mass region[1-3] related the E1 gamma-ray strength function to the tail of the giant dipole resonance, assuming it to be represented by a single Lorentzian function. In terms of the classical dipole sum rule, it was expressed as:

$$f_{E1}(E_\gamma) = 3.3 \times 10^{-6} \frac{NZ}{A} F_{SR} \frac{E_\gamma \Gamma_R}{(E_\gamma \Gamma_R)^2 + (E_\gamma^2 - E_R^2)^2} \quad (1)$$

where E_R and Γ_R are the energy and width of the giant dipole resonance and F_{SR} is the fraction of the sum rule that is exhausted. We developed systematics for E_R and Γ_R in cases where experimental data were lacking. From a study of elements ranging from As to Cd, we adopted the expression: $E_R = 35.4/A^{1/6}$ and we parameterized the width in terms of the nuclear deformation parameter, β_2 : $\Gamma_R = (A^{1/3}/1.227)(1. + 12.78 \beta_2^2)$. The expression for the giant dipole width reproduced the literature values to $\pm$ 10% or better in this mass region. To obtain values for F_{SR}, we carried out statistical model calculational fits to available experimental neutron capture cross-section data for 12 target nuclei from ^{75}As to ^{103}Rh. In these calculations, we assumed only dipole transitions, an M1 contribution to the capture width of $\sim$ 15%-20%, and the Brink-Axel energy dependence for the E1 transitions. The E1 strength functions extracted from these fits, when compared with those predicted by Eq. 1, yielded values for F_{SR}. In general, these values agreed quite well with those inferred from total integrated photoneutron data,[4] as shown in Fig. 1. The value of F_{SR} was somewhat mass dependent: about 0.75 for A = 90 and about 1.1 for A = 94. Two marked exceptions to the general trend were the compound nuclei ^{76}As and ^{104}Rh.

Further, for both of these cases, the experimental thermal neutron capture gamma-ray spectrum was much harder than that calculated. And while this earlier modeling successfully predicted the magnitude of (n,γ) and (p,γ) cross sections in this region, it failed, in general, to reproduce the observed hardness in associated gamma-ray spectra.[5] This was further illustrated by the study of the gamma-ray spectra for the ^{93}Nb(n,γ)

reaction.[3] It was found that the E1 strength function had to be modified by adding a small resonance around 5.5 MeV or by adding a step decrease below 4.5 MeV or by using different combinations of these two, to obtain the harder spectra indicated by experiment. With each modification the capture cross section was reproduced equally well.
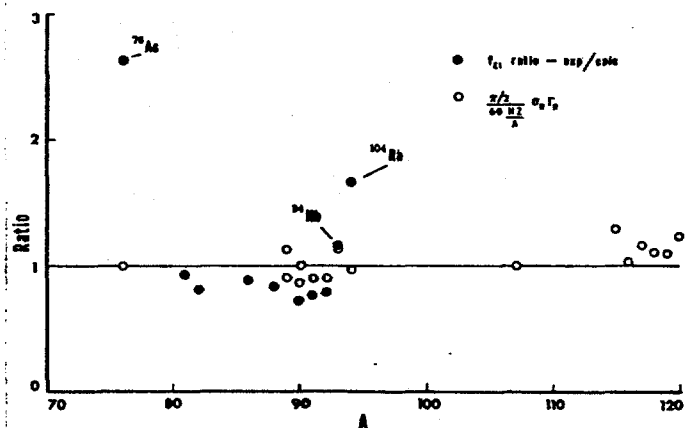

Fig. 1. Ratio of f_{E1} value (at E_γ = 3 MeV) extracted from (n,γ) cross-section measurements to that calculated with Eq. 1 vs. A (closed circles); and total, integrated photoneutron cross section[4] expressed in sum rule units vs. A (open circles).

The present re-investigation in the mass 90 region described in the following sections, makes use of the double-peak, energy-dependent Breit-Wigner (EDBW) model of the E1 strength function as outlined in the companion paper[6] in this conference. This model is tested to see if a consistent set of parameters can be obtained for this mass range which will yield a step in the low-energy tail of the E1 strength function that allows: (a) agreement with the photonuclear data at high energies; (b) the correct magnitude of Γ_γ to be obtained for agreement with neutron capture cross section data; and (c) the calculation of the observed hardness in the capture gamma-ray spectra.

Calculational Details

The double-peak, giant dipole parameters were computed making all of the assumptions listed in Ref. 6. This included the assumption that the integrated photonuclear absorption cross section is always 1.25 times the sum rule value. In Fig. 2 are shown the total integrated photoneutron cross sections obtained from the data available in Ref. 4 for V through Bi, expressed in sum rule units. Data from both single and double peak interpretations are included; connecting vertical lines indicate a range of data for the same nucleus. One sees that over most of the full mass range, the relation 1.25 times the sum rule is reasonable, although at around A = 90 and below this value appears to fall off.
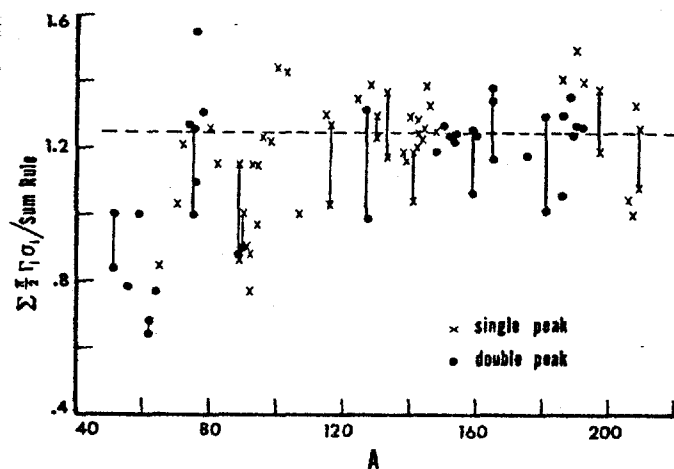

Fig. 2. Total, integrated photoneutron cross sections[4] expressed in sum rule units vs. A.

Remembering that the energy-dependent width is expressed as:

$$\Gamma(E_\gamma) = \Gamma_R \left(\frac{C + E_x}{C + E_\gamma}\right)\left(\frac{E_\gamma^2}{E_x}\right)\left(\frac{2}{E_x + E_R}\right) \qquad (2)$$

we will see that consistent results in this mass 90 range are obtained when E_x is 5 MeV and C ranges from 1 to 5 MeV. This is in agreement with the studies at higher A values.[6]

The latest versions of the statistical model nuclear reaction codes: STAPRE[7] and COMNUC[8] were used. The neutron optical model parameters used in the Y and Zr calculations were the [89]Y parameters of Lagrange.[9] Those used for the Nb and Rh calculations were Lagrange's [93]Nb parameters.[10] The As calculations were carried out using the neutron parameters of Moldauer.[11] Level densities were computed using the Gilbert-Cameron formalism,[12] as updated by Cook.[13] The constant temperature portion was adjusted to match discrete level input while the Fermi gas portion was adjusted to yield correct D_{obs} values where known.

Results for Nb, As, and Rh

In Fig. 3 is shown the computed capture gamma-ray spectrum (solid circles) for [93]Nb compared with the unnormalized, experimental spectrum of Orphan for thermal neutrons (histogram).[14] The calculated spectrum was obtained using the double-peak, EDBW model of the E1 strength function, with the energy-dependent width described by Eq. 2 where E_x = 5 MeV and C = 5 MeV. The insert shows various E1 strength functions for [94]Nb as a function of the gamma-ray energy: the short-dashed curve is the f_{E1} obtained using a single-peak Lorentz form with the [93]Nb parameters of Ref. 4; the solid and long-dashed curves are f_{E1}'s obtained using the present modeling. The solid curve was computed with an energy-dependent width parameterized with E_x = 5 MeV and C = 1 MeV; the long-dashed curve with a width where E_x = 5 MeV and C = 10 MeV. It should be noted that while all three of the EDBW f_{E1}'s described (where C = 1, 5, or 10 MeV) reproduced the experimental capture cross-section data of Poenitz[15] quite well for neutron energies of 0.3 MeV to 1.7 MeV, the f_{E1} with C = 5 MeV gave the best agreement with the measured gamma-ray spectrum.
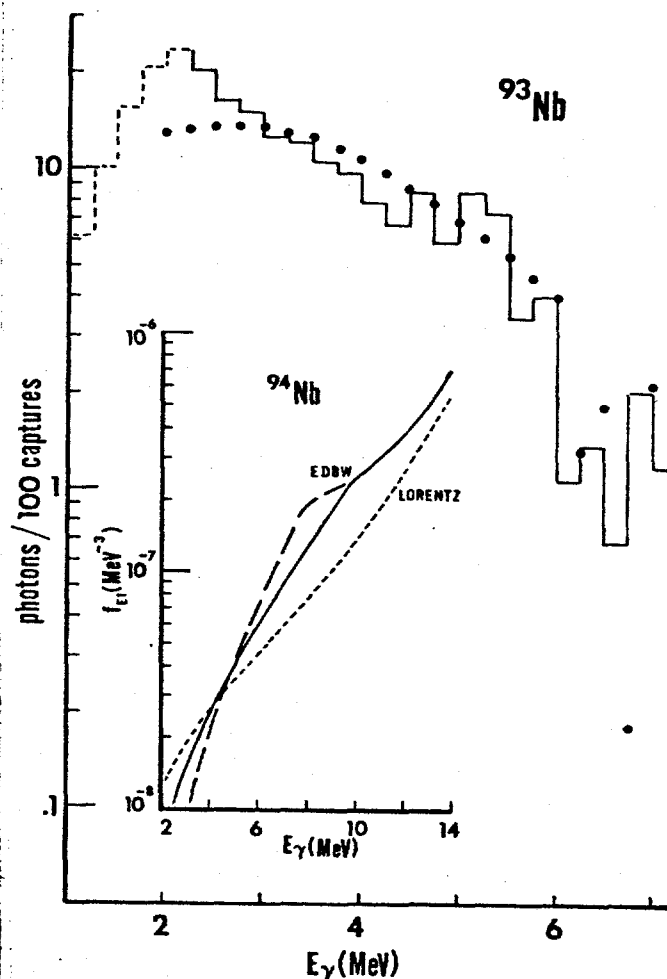

Fig. 3. Comparison of Orphan's[14] measured thermal neutron capture gamma-ray spectrum for [93]Nb (histogram) with that calculated via the double-peak, EDBW model (closed circles). Insert compares f_{E1}'s for [94]Nb: Lorentz form with parameters from Ref. 4 (short-dashed curve) and EDBW model with E_x = 5 MeV, C = 1 MeV (solid curve), with E_x = 5 MeV, C = 10 MeV (long-dashed curve).

Various calculated gamma-ray spectra for ^{75}As are shown in Fig. 4, again compared with the measured thermal neutron capture gamma-ray spectrum of Orphan (histogram).[14] The double-peak, EDBW model (solid circles) best reproduces the hardness observed in the spectrum, compared with the results obtained using a Lorentz form (open circles) or a Weisskopf formulation (open, inverted triangles) of the E1 strength function. The Lorentz form was computed with one of the sets of the double-peak, giant dipole parameters given in Ref. 4. The EDBW f_{E1} was calculated with an energy-dependent width where E_x = 5 MeV and C = 1 MeV. This same E1 strength function yielded the calculated capture cross section (solid curve) shown in Fig. 5, in good agreement with the more recently measured data sets (shown by the solid symbols).[16-20]
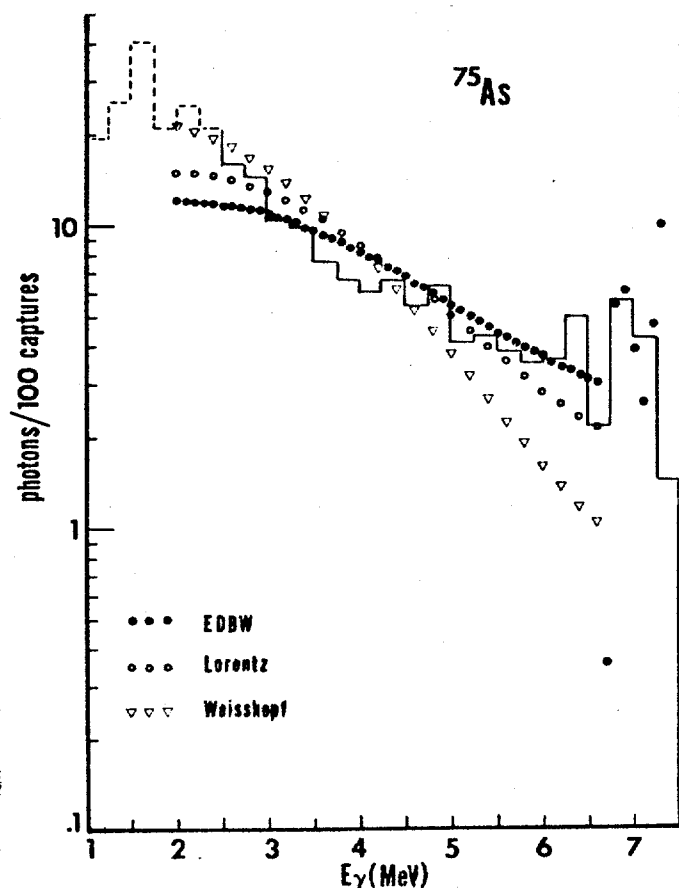

Fig. 5. The calculated (n,γ) cross section for ^{75}As (solid curve) compared with recent measurements[16-20] (solid symbols).

Fig. 4. Comparison of Orphan's[14] measured thermal neutron capture gamma-ray spectrum for ^{75}As (histogram) with calculations: double-peak, EDBW model (closed circles), Lorentz form (open circles) and Weisskopf form (inverted triangles).

In Fig. 6a is shown the computed neutron capture cross section for ^{103}Rh (solid curve) obtained with the present modeling of the E1 strength function. Again the energy-dependent width was described with E_x = 5 MeV and C = 1 MeV. The calculated cross section is in good agreement with the data of Macklin et al. (solid triangles, both upright and inverted)[17,21] and the data of Joly et al. (solid squares).[22] In Fig. 6b the calculated gamma-ray spectrum (solid hexagons) is compared with the measured thermal neutron capture gamma-ray spectrum of Orphan (histogram).[14] The double-peak, EDBW f_{E1}, as described, was used in the spectrum calculation and reproduces the observed hardness reasonably well.
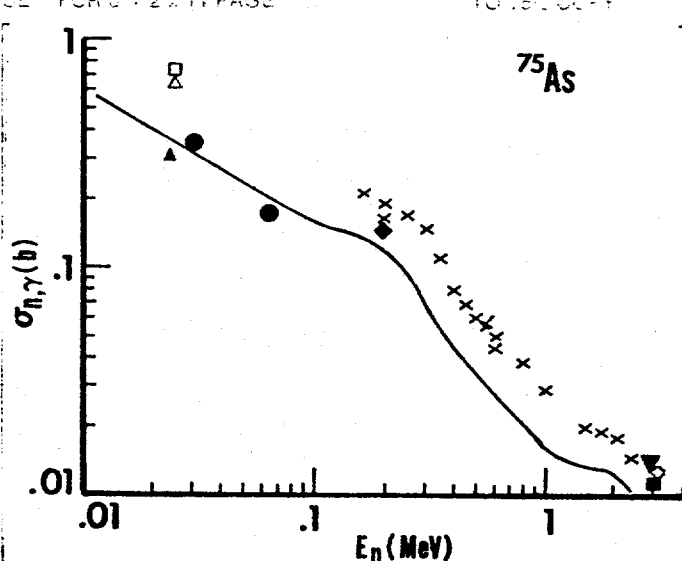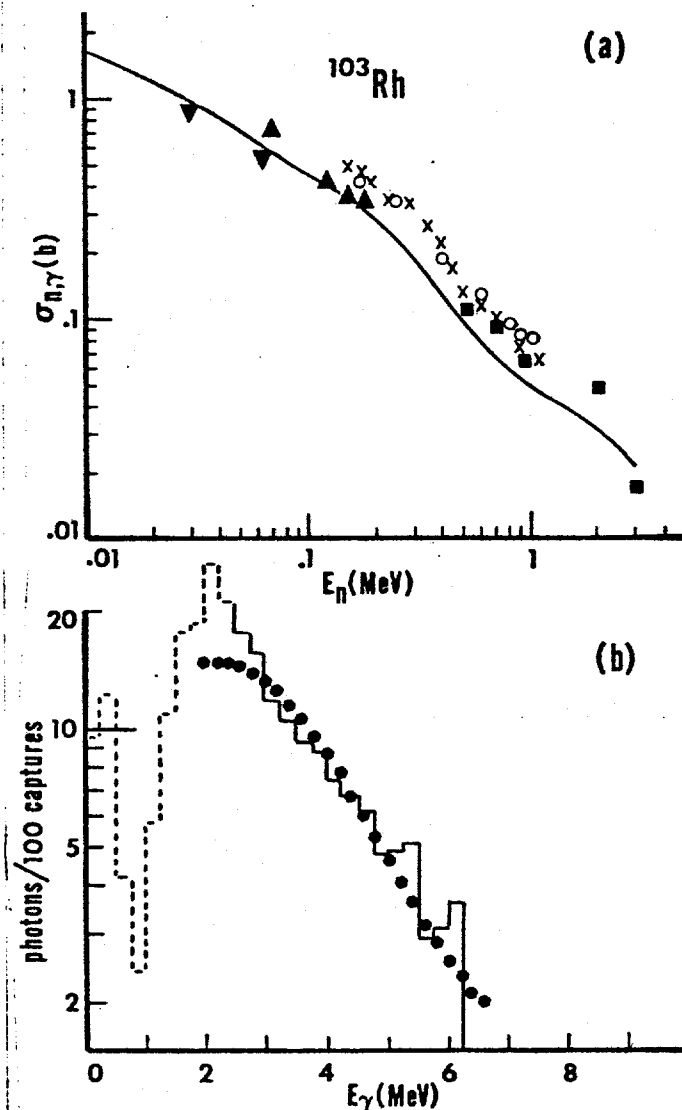

Fig. 6. a) Comparison of the calculated (n,γ) cross section for ^{103}Rh (solid curve) with measurements of Macklin et al.[17,21] (triangles) and of Joly et al.[22] (squares). b) Calculated thermal neutron capture gamma-ray spectrum for ^{103}Rh (solid hexagons) compared with Orphan's measurement[14] (histogram).

Results for Y and Zr

It appears that in the case of nuclei at or near the closed neutron shell, $N = 50$, the assumption breaks down that these nuclei can still be treated to some extent as prolate spheroids and that their E1 strength functions can be described by two, super-imposed giant dipole resonances. Our studies so far, for nuclei with $N = 50$ and 51, indicate that the double-peak, EDBW model overestimates the E1 strength function by a factor of two or more at some energies. This leads to neutron capture cross-section calculations that are too high.

In these cases, we do find that if all assumptions and systematics as described[6] are still used but that only the first, narrower resonance is employed to compute the energy-dependent Breit-Wigner E1 strength function, reasonable results are obtained. This may be seen in Fig. 7. Here is shown the single-peak, EDBW E1 strength function (solid curve) as it varies with the gamma-ray energy compared with experimental measurements and with data inferred from photoneutron experiments. The measured f_{E1} values are those of Axel et al. (solid circles)[23] and of Szeflinska et al. (open circles),[24] while the dashed curves were obtained from Lorentz formulations using the resonance parameter sets in Ref. 4. Again, using the single-peak, EDBW model to calculate the capture cross section for ^{89}Y and ^{90}Zr, the results shown in Fig. 8a and 8b are obtained. Both of the computed cross sections (solid curves) resulted from f_{E1}'s with energy-dependent widths where $E_x = 5$ MeV and $C = 1$ MeV. The calculated cross sections are in good agreement with the various sets of experimental data.[21,25-30]
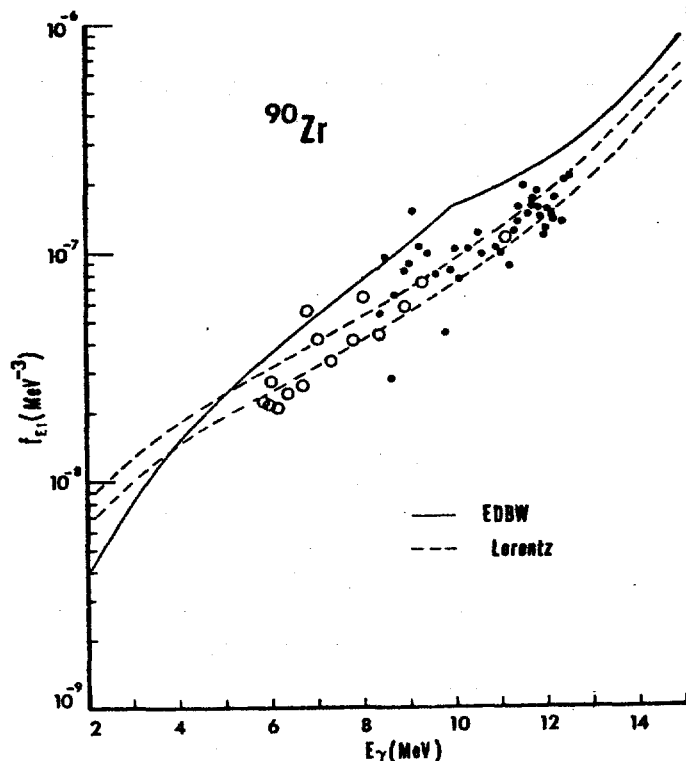

Fig. 8. The calculated (n,γ) cross sections for ^{89}Y and ^{90}Zr (solid curves) compared with measurements.[21,25-30]

Fig. 7. Comparison of the single-peak, EDBW E1 strength function for ^{90}Zr vs. E_γ (solid curve) with: measurements of Axel et al.[23] (solid circles) and of Szeflinska et al.[24] (open circles); Lorentz form with parameters from Ref. 4 (dashed curves).
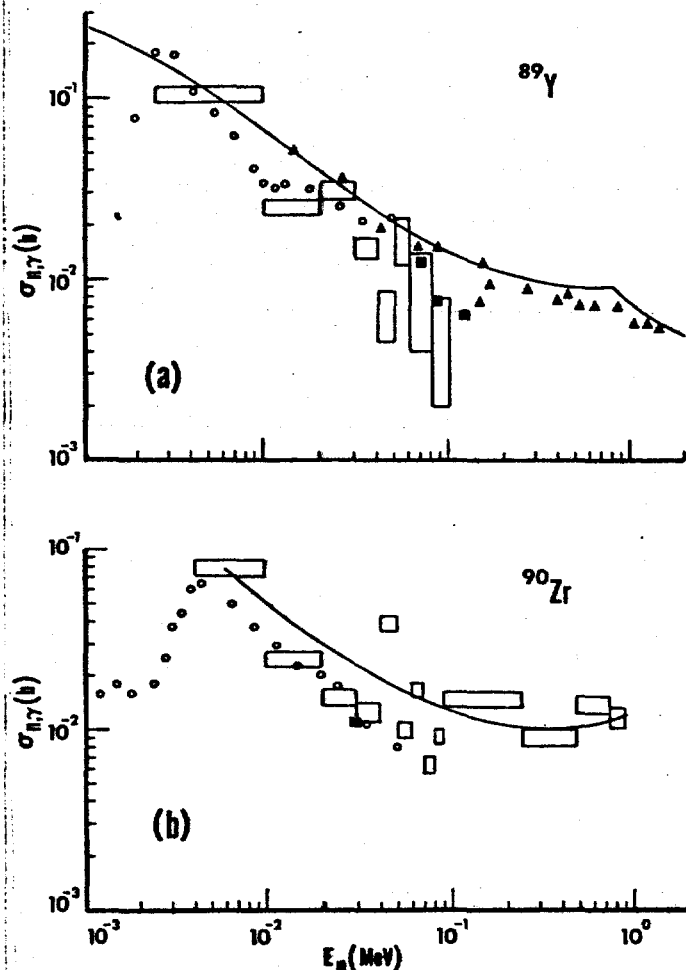
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